# Measurement of Higgs Couplings and their Implications for New Physics Scales

Milada Margarete Mühlleitner (KIT)
Coll. with Englert, Freitas, Plehn, Rauch, Spira and Walz

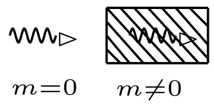
**SUSY 2014**

**University of Manchester**
**21-26 July 2014**

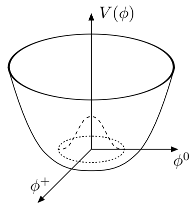
# What Can We Learn From Higgs Physics?

## Test of the Higgs mechanism

- Mass, Total Width – $m, \Gamma$
- Interaction with a scalar Higgs with $v \approx 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$




- Spin and parity quantum numbers – $J^{PC}$
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$




✐ Is it *the* Standard Model *Higgs* boson?

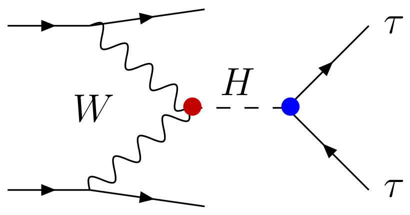
✐ Is it the harbinger of New Physics?

# $\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

## Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

E.g.:




$\sim \Gamma_{WW} \frac{\Gamma(H \to \tau\tau)}{\Gamma_{\text{tot}}}$ (narrow width approximation)

# Determination of the Higgs Boson Couplings

## Strategy

Combination of the production and decay channels ⇒ decay rates, absolute couplings

$$\sigma_{\rm prod}(H)\times \text{BR}(H\to XX) \sim \Gamma_{\rm prod}\times\frac{\Gamma_{\rm decay}}{\Gamma_{\rm tot}}$$

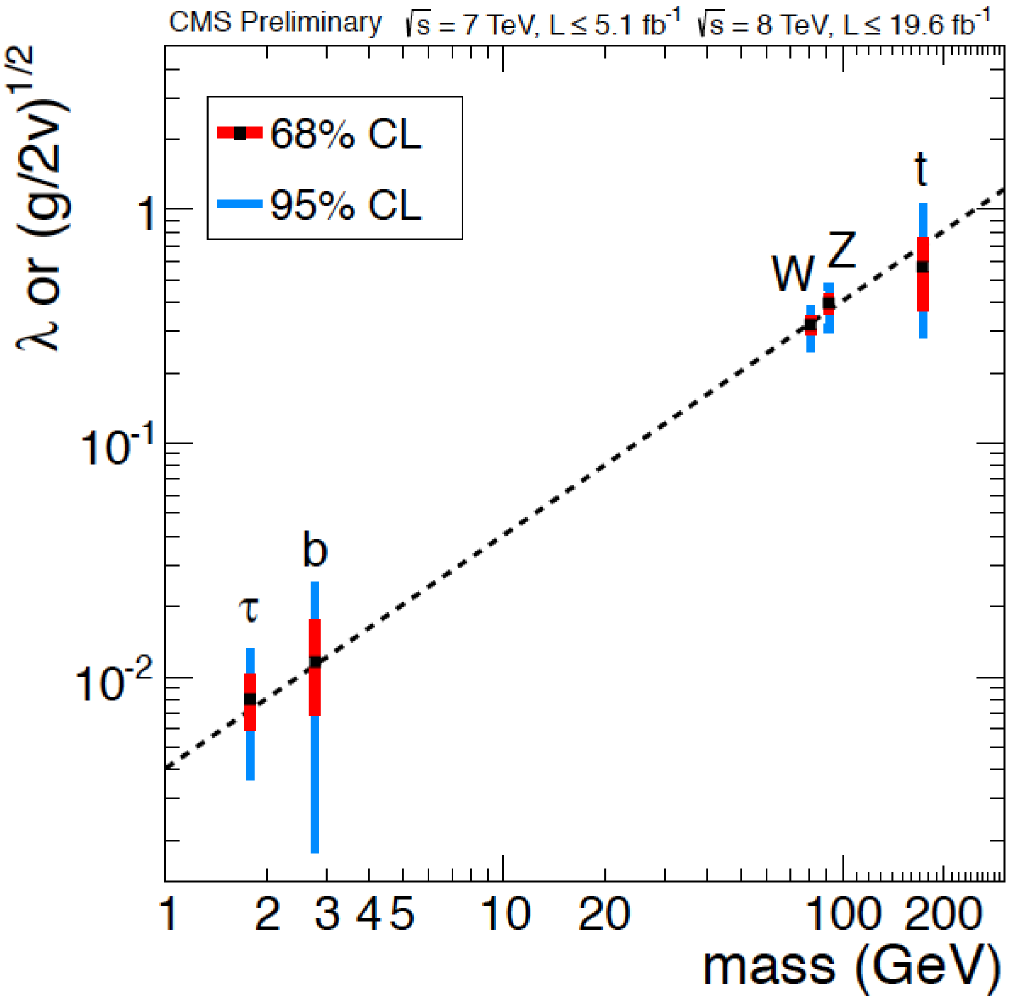
## Coupling measurement at the LHC

* Determination of total width impossible w/o further assumptions
* Not all final states are accessible
* ⇒ Only ratios of couplings can be measured
* ⇒ Perform fits to reduced signal strengths $\mu$

$$\mu = \frac{\sigma\times\text{BR}}{(\sigma\times\text{BR})_{\rm SM}}$$

# $\mathcal{E}$xperimental $\mathcal{S}$tatus: $\mathcal{C}$ouplings

CMS-PAS-HIG-13-005



# What Can We Learn From Coupling Measurements?

- ***The Standard Model Higgs Boson***
  - ◇ Test relation $g_{hXX} \sim m_X$ predicted by Higgs mechanism

- **Deviations from SM couplings $\longleftarrow$ New Physics**
  - ◇ modified Higgs properties through mixing effects with other scalars or mixture between elementary and composite state in case of a composite particle (partial compositeness)
  - ◇ modified Higgs properties through loop effects or effective low-energy operators (strong interaction)

What is the Scale of New Physics that can be Probed?

## $\mathcal{T}$heoretical $\mathcal{A}$pproach to $\mathcal{C}$oupling $\mathcal{E}$xtraction

**Theoretical approach** couplings extracted from experimental $\mu = (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$ values

- $\Rightarrow$ Need Lagrangian to define the meaning of the couplings
- Effective Lagrangian w/ modified Higgs couplings $\to$ signal rates $\to$ fit to experimental $\mu$ values

**General Coupling Modification**

- absolute value and tensor structure
- $\Rightarrow$ determination of couplings and CP properties cannot be treated separately in general
- $\rightsquigarrow$ change of distributions $\leftrightarrow$ no simple rescaling of MC predictions
- $\Rightarrow$ LHC Higgs XS WG: interim framework

◇ **For further work, see:**

D.Carmi, A.Falkowski, E.Kuflik, T.Volansky; D.Carmi, A.Falkowski, E.Kuflik, T.Volansky, J.Zupan; A.Azatov, R.Contino, J.Galloway; Espinosa, Grojean, MMM, Trott; P.Giardino, K.Kannike, M.Raidal, A.Strumia; J.Ellis, T.You; M.Klute, R.Lafaye, T.Plehn, M.Rauch, D.Zerwas; M.Montull, F.Riva; I.Low, J.Lykken, G.Shaugnessy; T.Corbett, O.Eboli, J.González-Fraile, M.C. González-Garcia; Banerjee, Mukhopadhyay, Mukhopadhyaya; Cao eal; Bélanger, Dumont, Ellwanger, Gunion, Kraml; ...

# (I) $\mathcal{N}$on-$\mathcal{L}$inear $\mathcal{E}$ffective $\mathcal{L}$agrangian

◇ **Field content:** SM with scalar field $h$; SM: $\kappa_i = 1, \overline{\kappa}_i = 0$

Contino eal '10,'12; Azatov eal; Alonso eal; Brivio eal; Elias-Miró eal; Isidori eal; Buchalla eal

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_3 \left(\frac{m_h^2}{2v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + \kappa_\psi \frac{h}{v} + \ldots\right)$$

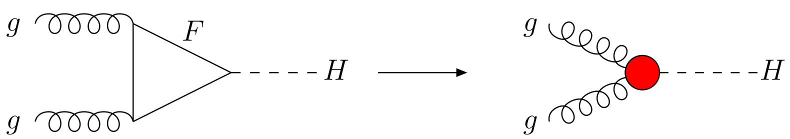
$$+ m_W^2\, W_\mu^+ W^{-\,\mu}\left(1 + 2\kappa_W \frac{h}{v} + \ldots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2\kappa_Z \frac{h}{v} + \ldots\right) + \ldots$$

$$+ \left(\frac{\bar{\kappa}_{WW}\,\alpha}{\pi} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\bar{\kappa}_{ZZ}\,\alpha}{2\pi} Z_{\mu\nu}Z^{\mu\nu} + \frac{\bar{\kappa}_{Z\gamma}\,\alpha}{\pi} Z_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_{\gamma}\,\alpha}{2\pi}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_g\,\alpha_s}{12\pi} G^a_{\mu\nu}G^{a\mu\nu}\right)\frac{h}{v}$$

$$+ \left(\left(\bar{\kappa}_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + \bar{\kappa}_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \bar{\kappa}_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\frac{h}{v} + \ldots$$

◇ **Remarks:** $*$ Valid for $h$ being singlet or doublet

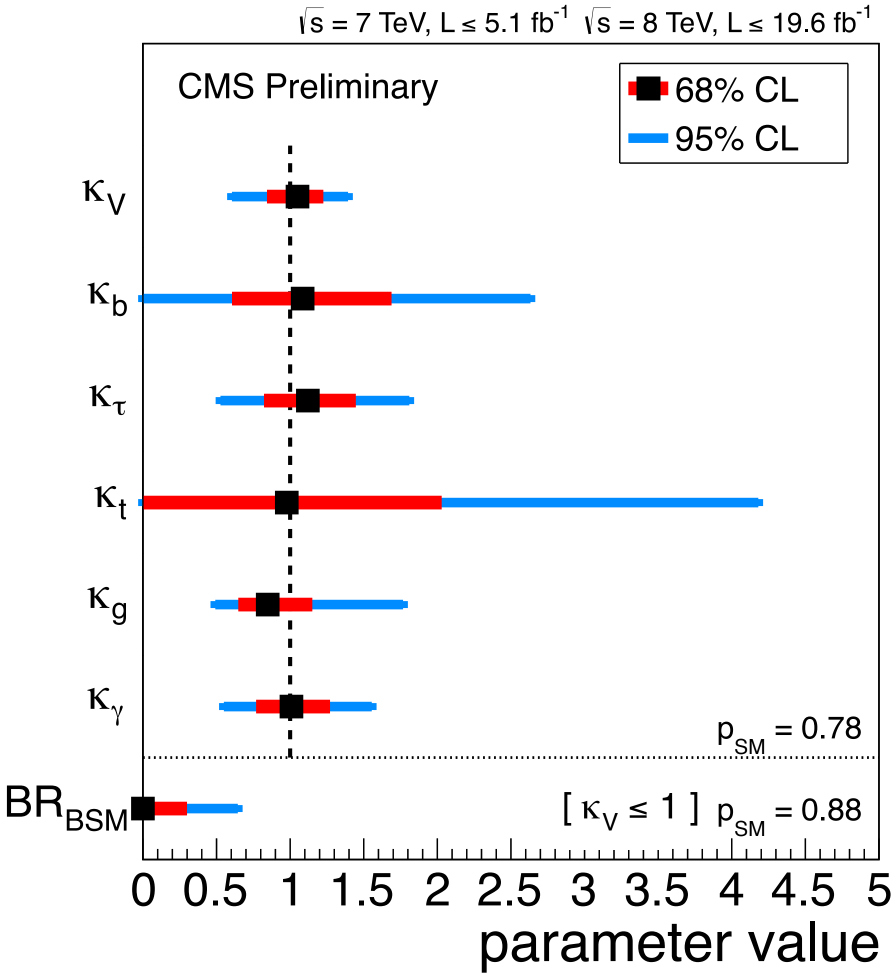
$*$ $\overline{\kappa}_{g,\gamma,Z\gamma}$ parametrize new physics in the $hgg$, $h\gamma\gamma$ and $hZ\gamma$ loop couplings

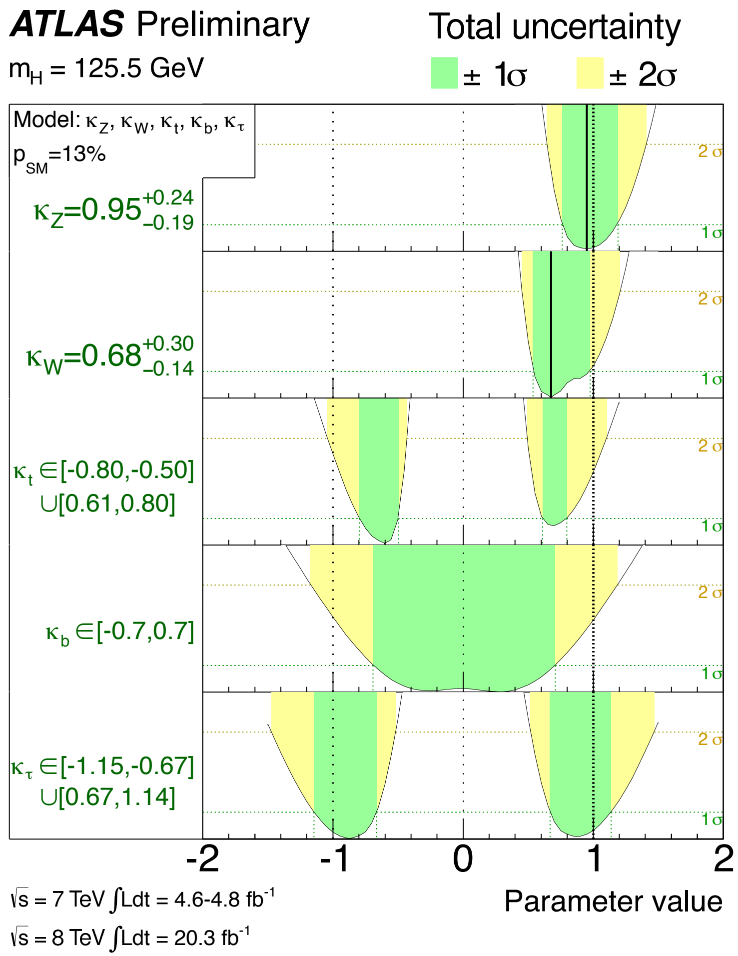


# $\mathcal{S}$tatus: $\mathcal{C}$oupling $\mathcal{S}$cale $\mathcal{F}$actor $\mathcal{M}$easurements

CMS Collaboration

ATLAS-CONF-2014-009



## (II) $\mathcal{E}$ffective $\mathcal{L}$agrangian for a $\mathcal{L}$ight $\mathcal{H}$iggs-$\mathcal{L}$ike $\mathcal{S}$calar

- **Natural Mechanisms for EWSB suggest**
  - ◇ New physics at some scale $\Lambda \sim \mathcal{O}(\text{TeV})$
  - ◇ New physics generates deviations in SM Higgs physics

- **Convenient framework for model-independent analysis:** Effective Lagrangian Approach

  Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal;Hagiwara,Ishihara,Szalapski,Zeppenfeld;Giudice eal

  - ∗ assume few basic principles (e.g. field content, SM gauge symmetries)
  - ∗ parametrize SM deviations by higher-dimensional operators built of SM fields
  - ∗ Operators = low-energy remnants of heavy NP integrated out at $\Lambda \Rightarrow$
  - ∗ Operators suppressed by scale $\Lambda$

- **Example:** $SU(3) \times SU(2) \times U(1)$ invariance $\rightsquigarrow$ leading NP effects described by $D = 6$ operators

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

# $\mathcal{S}$cales $\mathcal{P}$robed $\mathcal{I}$n $\mathcal{C}$oupling $\mathcal{M}$easurements

- **Use expansions in higher dimensional operators** to describe coupling deviation $\rightsquigarrow$

$$g_{hXX} = g_{hXX}^{\mathsf{SM}}[1+\Delta] \;:\; \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\Lambda \gg v =$ characteristic scale of Beyond the SM Physics

[caveat: non-decouplings effects]

- **Scales to be probed in Mixing Effects**

| | | | |
|---|---|---|---|
| LHC coupling precision: | $4-15\%$ | $\rightsquigarrow$ | $\Lambda = 640$ GeV...$1.2$ TeV |
| HL-LHC coupling precision: | $2-10\%$ | $\rightsquigarrow$ | $\Lambda = 780$ GeV...$1.7$ TeV |

- **Scales to be probed in Loop Effects**

  additional loop suppression factor $\rightsquigarrow \Delta = \frac{v^2}{16\pi^2\Lambda^2}$

  $\Rightarrow$ for $\Delta = 0.02$ scale probed: $\Lambda \approx 140$ GeV

# Coupling Accuracies

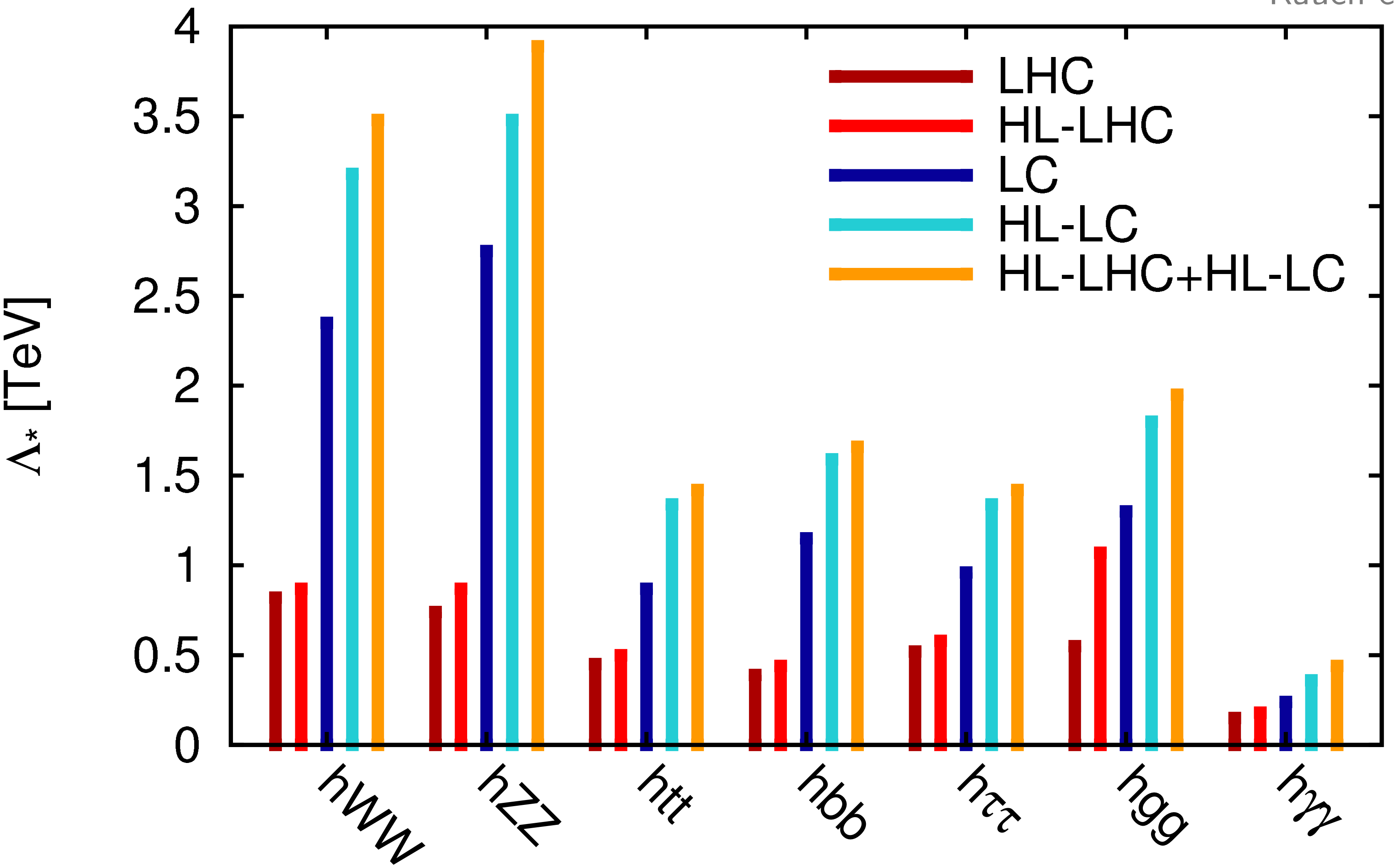
Englert eal

| coupling | LHC | HL-LHC | LC | HL-LC | HL-LHC + HL-LC |
|---|---|---|---|---|---|
| $hWW$ | 0.09 | 0.08 | 0.011 | 0.006 | 0.005 |
| $hZZ$ | 0.11 | 0.08 | 0.008 | 0.005 | 0.004 |
| $htt$ | 0.15 | 0.12 | 0.040 | 0.017 | 0.015 |
| $hbb$ | 0.20 | 0.16 | 0.023 | 0.012 | 0.011 |
| $h\tau\tau$ | 0.11 | 0.09 | 0.033 | 0.017 | 0.015 |
| $h\gamma\gamma$ | 0.20 | 0.15 | 0.083 | 0.035 | 0.024 |
| $hgg$ | 0.30 | 0.08 | 0.054 | 0.028 | 0.024 |
| $h_{\text{invis}}$ | — | — | 0.008 | 0.004 | 0.004 |

* accuracy at 68% CL; deviations: $g = g_{\text{SM}}[1 \pm \Delta]$
* LHC/HL-LHC: $\int \mathcal{L} = 300$ fb$^{-1}$ and 3000 fb$^{-1}$
* LC/HL-LC: 250+500 GeV/250+500 GeV+1 TeV, $\int\mathcal{L} = 250 + 500$ fb$^{-1}$/1150+1600+2500 fb$^{-1}$

# $\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales

Rauch et al.



## $\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales (loop, coupling factors factored out)

- **Effective New Physics scales $\Lambda_*$** extracted from coupling measurements

| $\Lambda_*$ [TeV] | LHC | HL-LHC | LC | HL-LC | HL-LHC + HL-LC |
|---|---|---|---|---|---|
| $hWW$ | 0.82 | 0.87 | 2.35 | 3.18 | 3.48 |
| $hZZ$ | 0.74 | 0.87 | 2.75 | 3.48 | 3.89 |
| $htt$ | 0.45 | 0.50 | 0.87 | 1.34 | 1.42 |
| $hbb$ | 0.39 | 0.44 | 1.15 | 1.59 | 1.66 |
| $h\tau\tau$ | 0.52 | 0.58 | 0.96 | 1.34 | 1.42 |
| $hgg$ | 0.55 | 1.07 | 1.30 | 1.80 | 1.95 |
| $h\gamma\gamma$ | 0.15 | 0.18 | 0.24 | 0.36 | 0.44 |

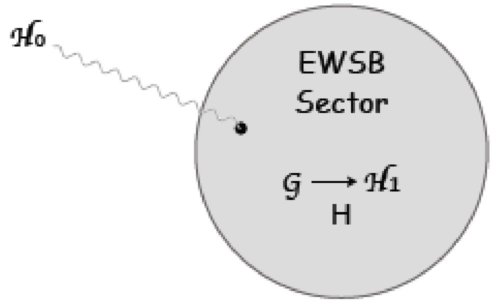
Loop-induced couplings to gluons and photons contain only the contribution of the contact terms

# $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson

Kaplan,Georgi; Dimopoulos eal; Dugan eal

- **Bound state from a Strongly Interacting Sector not much above weak scale**

- **How can we obtain a light composite Higgs?**




Higgs: Pseudo-Goldstone boson of strongly interacting sector

Global symmetry of strong sector $\mathcal{G}$ $\xrightarrow{\text{spontaneously broken at } f}$ subgroup $\mathcal{H}_1$

$\mathcal{G}/\mathcal{H}_1$: contains Higgs boson as Nambu-Goldstone Boson

- **Continuous interpolation between the SM and Technicolor:**

$\xi = 0$ SM limit $\longleftarrow$ $\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$ $\longrightarrow$ $\xi = 1$ "Technicolor" limit

strong sector resonances decouple, except boson

boson deccouples, vector resonances like in TC

- **No hierarchy problem** EWSB potential generated at one-loop through gauge and top loops



Cartoon from R.Contino [1005.4269]

# $\mathcal{S}$trongly $\mathcal{I}$nteracting $\mathcal{L}$ight $\mathcal{H}$iggs ($\mathcal{SILH}$)

- **SILH Lagrangian:** first term of an expansion in $\xi = v^2/f^2$ [$f$: typical scale of strong sector]
  Higgs couplings modified in terms of $\xi$ Giudice,Grojean,Pomarol,Rattazzi

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz

| $\xi$ | LHC | HL-LHC | LC | HL-LC | HL-LHC+HL-LC |
|---|---|---|---|---|---|
| universal | 0.076 | 0.051 | 0.008 | 0.0052 | 0.0052 |
| non-universal | 0.068 | 0.015 | 0.0023 | 0.0019 | 0.0019 |
| $f$ [TeV] | | | | | |
| universal | 0.89 | 1.09 | 2.82 | 3.41 | 3.41 |
| non-universal | 0.94 | 1.98 | 5.13 | 5.65 | 5.65 |

universal: fermions in spinorial representation Agashe,Contino,Pomarol
non-universal: fermions in fundamental representation Contino,Da Rold,Pomarol

# $\mathcal{C}$omputer $\mathcal{T}$ool for $\mathcal{H}$iggs $\mathcal{D}$ecay $\mathcal{W}$idths

- **Implementation for Higgs decay widths:** `eHDECAY`

  R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira

  URL: http://www.itp.kit.edu/~maggie/eHDECAY/

- **Implemented Parametrisations**

| | |
|---|---|
| SILH: | strongly interacting light Higgs boson, SU(2) doublet |
| MCHM4,5: | minimal composite Higgs models |
| non-linear: | expansion, allows large couplg deviations from SM |

# $\mathcal{P}$rogram eHDECAY

## eHDECAY

The program eDHECAY is a modified version of the latest release of HDECAY 5.10.
It allows for the calculation of the partial decay widths and branching ratios of a
Higgs-like boson within different parametrisations of the Lagrangian:
the non-linear Lagrangian, the SILH Lagrangian and the
composite Higgs parametrization according to MCHM4 or MCHM5.

Released by: Roberto Contino, Margherita Ghezzi, Christophe Grojean, Margarete Mühlleitner and Michael Spira
Program: eHDECAY obtained from extending HDECAY 5.10

When you use this program, please cite the following references:

| | |
|---|---|
| eHDECAY: | R. Contino, M. Ghezzi, C. Grojean, M. Mühlleitner, M. Spira, in arXiv 1303.3876 |
| HDECAY: | A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56 |
| An update of HDECAY: | A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643 |

### Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to margherita.ghezzi@roma1.infn.it or margarete.muehlleitner@kit.edu.

### Downloading the files needed for eHDECAY:

# $\mathcal{M}$ixing $\mathcal{E}$ffects: $\mathcal{H}$iggs $\mathcal{P}$ortal

- **Higgs Portal**

  [Schabinger,Wells; Bowen,Cui,Wells; Foot,Lew,Vokas; Chacko,Goh,Harnik; Barbierie,Gregoire,Hall; Patt,Wilczek; Strassler,Zurek; Barger eal; Lebedev,Lee; Chang,Ng,Wu; Kanemura eal; Bock eal; Binot,van der Bij]

  ∗ Hidden sector with complex structure (e.g. containing DM candidate - dark world)

  ∗ Higgs sector communicates widh hidden sector through renormalizable quartic interaction

  Higgs Portal : $\mathcal{L}_p = -\eta|\phi_s|^2|\phi_d|^2$ $\quad\quad$ $\phi_s$ SM field, $\phi_d$ dark Higgs field

  ∗ Mass eigen-fields $s_1, d_1$ mixtures of current fields

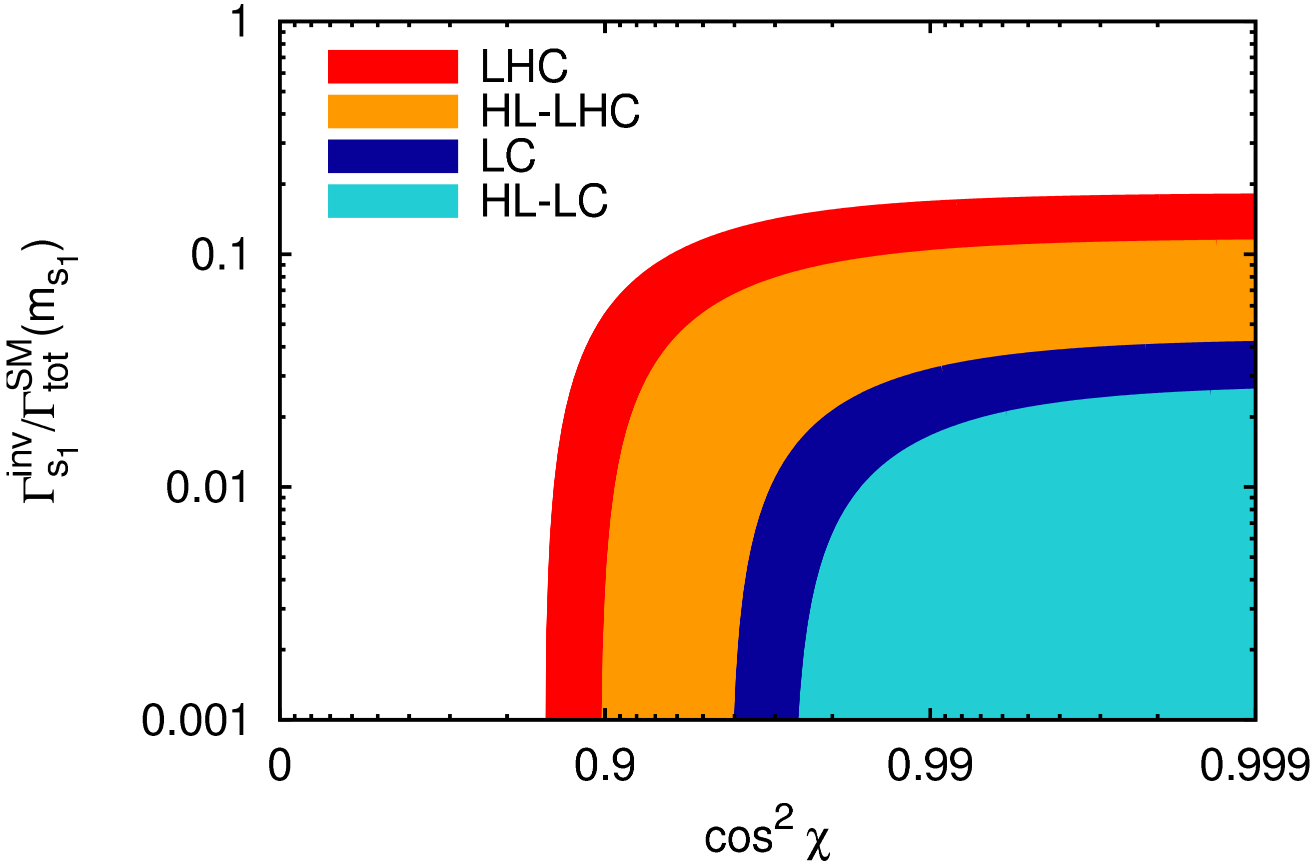
$$
\begin{aligned}
s_1 &= \cos\chi s + \sin\chi d \\
d_1 &= -\sin\chi s + \cos\chi d
\end{aligned}
$$

  ∗ Couplings of SM-like Higgs boson modified universally by mixing angle

$$
g_{s_1} = \cos\chi\, g_h^{\mathrm{SM}}
$$

# $\mathcal{B}$ounds on $\mathcal{I}$nvisible $\mathcal{W}$idth

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz arXiv:1403.7191




* SM Higgs $s_1$ decays into light dark sector particles $\leadsto \Gamma_{\text{inv}}(s_1)$
* derived limits $\Gamma^{\text{inv}}_{s_1}/\Gamma^{\text{SM}}_{\text{tot}} \lesssim 0.11...0.18$ (LHC), $\Gamma^{\text{inv}}_{s_1}/\Gamma^{\text{SM}}_{\text{tot}} \lesssim 0.04...0.11$ (HL-LHC)

# $\mathcal{M}$ixing $\mathcal{E}$ffects – 2HDM

- **$\rho$–parameter exp close to 1** $\rightsquigarrow$ extensions of Higgs sector by $SU(2)$ singlet or doublet

- **2HDM potential** assuming CP-conservation and global $\mathbb{Z}_2$ discrete symmetry $[\phi_1 \to -\phi_1]$

  Flores,Sher; Gunion et al; Lee; Branco et al; Gunion,Haber

$$V = m_{11}|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + \text{h.c}) + \lambda_1|\phi_1|^4 + \lambda_2|\phi_2|^4$$
$$+ \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \frac{1}{2}\lambda_5[(\phi_1^\dagger\phi_2)^2 + \text{h.c}]\,.$$

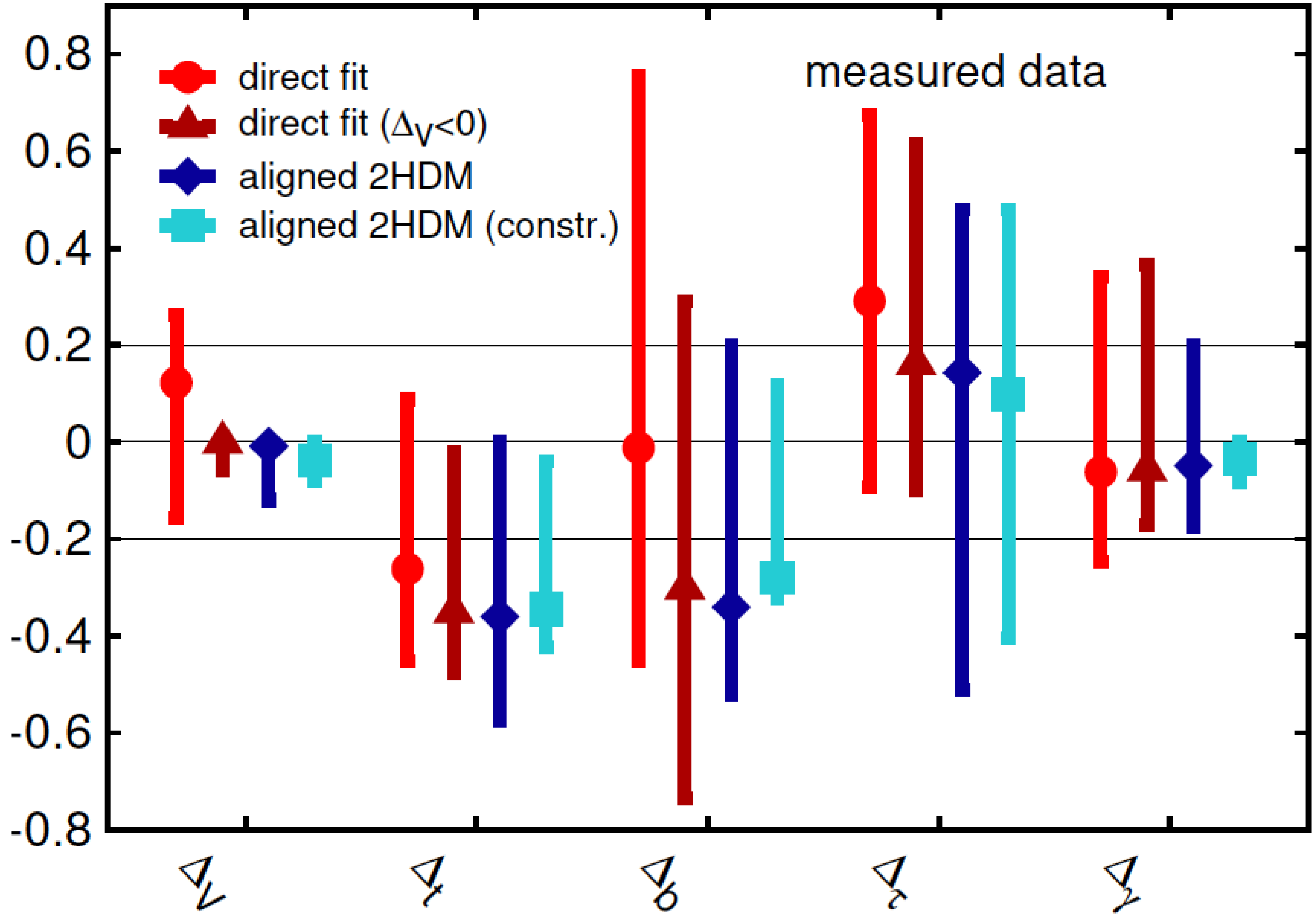
- **Couplings to fermions**
  - ◇ type I: all fermions couple only to $\phi_2$;
  - ◇ type II: up-/down-type fermions couple to $\phi_2/\phi_1$, respectively; $\rightarrow$ MSSM
  - ◇ lepton-specific: quarks couple to $\phi_2$ and charged leptons couple to $\phi_1$;
  - ◇ flipped: up-type quarks and leptons couple to $\phi_2$ and down-type quarks couple to $\phi_1$.

- **Higgs sector after EWSB** CP-even neutral: $h^0, H^0$, CP-odd neutral; $A^0$, charged $H^\pm$

# $\mathcal{F}$it to $\mathcal{C}$ouplings of $\mathcal{A}$ligned 2HDM

$g_X = g_X^{\text{SM}}(1 + \Delta_X)$

Rauch et al.



# HDECAY for Two Higgs Doublet Models

This program is a modified version of HDECAY Version 5.11.
It allows for the calculation of the partial decay widths and branching ratios in the 2HDM.

Released by: Abdelhak Djouadi, Jan Kalinowski, Margarete Mühlleitner and Michael Spira
Program: HDECAY for 2HDM based on HDECAY 5.11

When you use this program, please cite the following references:

| | |
|---|---|
| Manual: | R. Harlander, M. Muhlleitner, J. Rathsman, M. Spira, O. Stal, arXiv:1312.5571 [hep-ph] |
| HDECAY: | A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56 |
| An update of HDECAY: | A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643 |

## Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications concerning the 2HDM version, send an E-mail to margarete.muehlleitner@kit.edu.
- Modifs/corrected bugs are indicated explicitly in this file.

## Downloading the files needed for HDECAY for 2HDM:

- hdecay2hdm.tar.gz contains the program package files: the input file hdecay.in; hdecay.f, dmb.f, elw.f, feynhiggs.f, haber.f, hgaga.f, hgg.f, hsqsq.f, susylha.f; a makefile for the compilation.

# *Further 2-Higgs-Doublet-Model Programs*

- **Further Programs:**
  - ∗ Decay program `2HDMC` — Eriksson,Rathsman,Stål
  - ∗ Production program `SusHi` — Harlander,Liebler,Mantler
  - ∗ Production program `HIGLU` — Spira

- **Discussion and comparison, see:** Harlander,MMM,Rathsman,Spira,Stål, 1312.5571

# The MSSM Higgs Sector

**MSSM Higgs sector** – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even $h, H$ neutral, CP-odd $A$ charged $H^+, H^-$

**Higgs masses**

$$M_h \lesssim 140\ \text{GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v) \ldots 1\ \text{TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;Harlander et al
Degrassi et al;Kant et al;...

**Decoupling limit:**

$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

$M_h \rightarrow$ max. value, $\tan\beta$ fixed; $h$ becomes SM-like

**Modified couplings with respect to the SM:** (decoupling limit Gunion,Haber)

| $\Phi$ | $g_{\Phi u\bar{u}}$ | $g_{\phi d\bar{d}}$ | $g_{\Phi VV}$ |
|---|---|---|---|
| $h$ | $c_\alpha/s_\beta \rightarrow 1$ | $-s_\alpha/c_\beta \rightarrow 1$ | $s_{\beta-\alpha} \rightarrow 1$ |
| $H$ | $s_\alpha/s_\beta \rightarrow 1/\text{tg}\beta$ | $c_\alpha/c_\beta \rightarrow \text{tg}\beta$ | $c_{\beta-\alpha} \rightarrow 0$ |
| $A$ | $1/\text{tg}\beta$ | $\text{tg}\beta$ | 0 |

$\tan\beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$

$g_{\Phi dd} \uparrow$

$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

# $\mathcal{D}$ecoupling $\mathcal{L}$imit

- **Partial widths of SM-like light state in the decoupling limit:**

$$\frac{\Gamma_{\mathsf{SUSY}}[h^0 \to VV^*]}{\Gamma_{\mathsf{SM}}[h \to VV^*]} \approx 1 - \frac{m_Z^4 \sin^2 2\beta}{m_{A^0}^4} (\cos 2\beta + R_t)^2 ,$$

$$\frac{\Gamma_{\mathsf{SUSY}}[h^0 \to uu]}{\Gamma_{\mathsf{SM}}[h \to uu]} \approx 1 + \frac{4m_Z^2 \cos^2 \beta}{m_{A^0}^2} (\cos 2\beta + R_t) ,$$

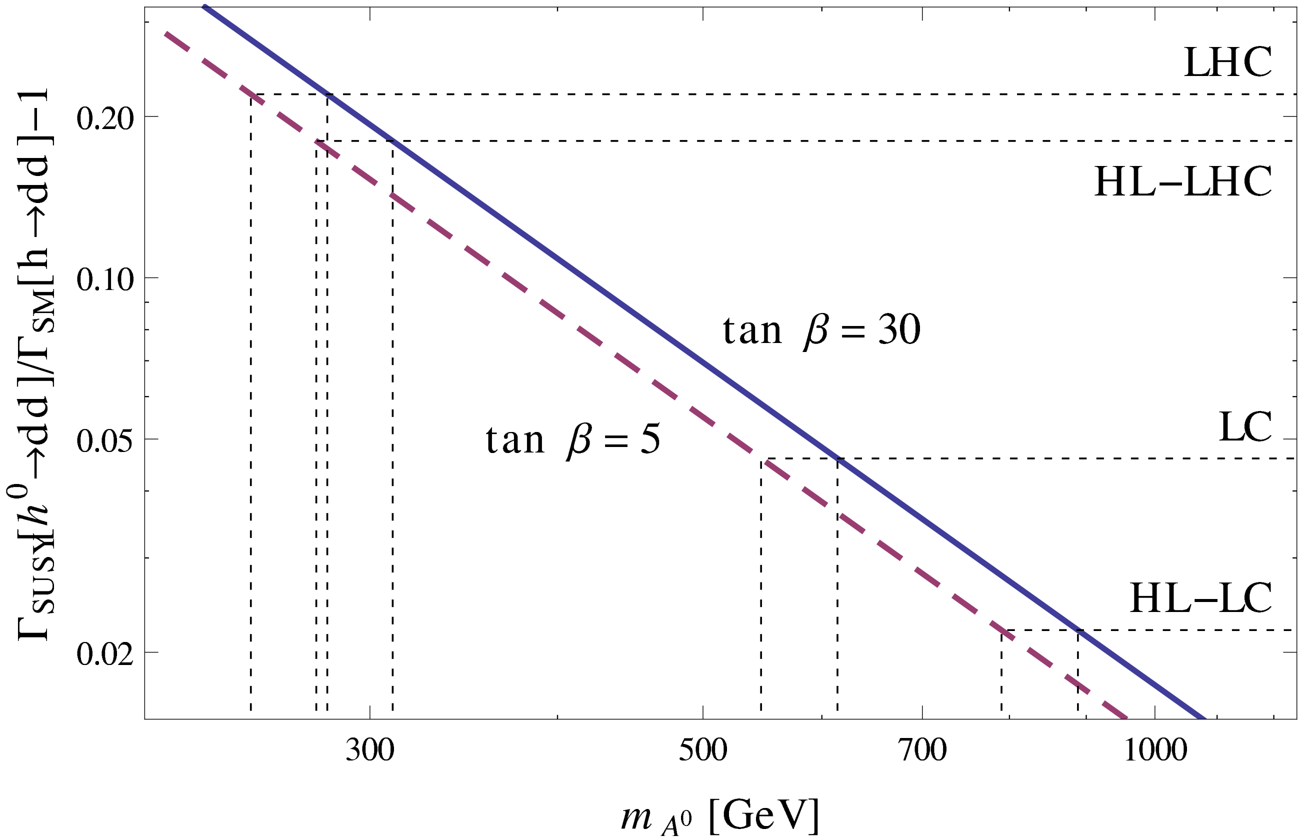
$$\frac{\Gamma_{\mathsf{SUSY}}[h^0 \to dd]}{\Gamma_{\mathsf{SM}}[h \to dd]} \approx 1 - \frac{4m_Z^2 \sin^2 \beta}{m_{A^0}^2} (\cos 2\beta + R_t)$$

- **SUSY radiative corrections dominated by top/stop loop contributions**

$$R_t \approx \frac{3(g^2 + g'^2)}{16\pi^2 \sin^2 \beta} \frac{m_t^4}{m_Z^4} \left[ \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + (A_t - \mu \cot 2\beta) \frac{A_t - \mu \cot \beta}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \log \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right.$$
$$\left. + (A_t^2 - \mu^2 - 2A_t \mu \cot 2\beta) \left( \frac{A_t - \mu \cot \beta}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \right)^2 \left( 1 - \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \log \frac{m_{\tilde{t}_1}}{m_{\tilde{t}_2}} \right) \right]$$

# $\mathcal{L}$imits on $\mathcal{H}$eavy $\mathcal{MSSM}$ $\mathcal{M}$asses

Englert eal '14




- $*$ $m_{\tilde{t}_1} m_{\tilde{t}_2} = 1$ TeV$^2$, $A_t - \mu \cot\beta \ll m_{\tilde{t}_i}$
- $*$ derived limits $m_{A^0} \gtrsim 250$ GeV (LHC),
  $m_{A^0} \gtrsim 280$ GeV/ $\gtrsim 380$ GeV (HL-LHC/CMS [1307.7135])

Englert,Freitas
MMM,Plehn
Rauch,Spira,Walz

| | Scenario/framework | LHC | HL-LHC | LC | HL-LC |
|---|---|---|---|---|---|
| Mixing effects | Higgs portal | 0.23 | 0.28 | 0.44 | 0.56 |
| | 2HDM type-II ($\tan\beta \approx 1$) | 0.52 | 0.58 | 1.15 | 1.6 |
| | 2HDM type-II ($\tan\beta \approx 10$) | 0.33 | 0.36 | 0.7 | 1.0 |
| Effective interactions | $D = 6$ effective operators: | | | | |
| | $hVV$ | 0.78 | 0.87 | 2.6 | 3.3 |
| | $hff$ | 0.45 | 0.50 | 1.0 | 1.4 |
| | $hgg$ contact | 0.55 | 1.1 | 1.3 | 1.8 |
| | $h\gamma\gamma$ contact | 0.15 | 0.18 | 0.24 | 0.36 |
| | Strong interactions | 0.9 | 1.1–2.0 | 2.8–5.1 | 3.4–5.6 |
| Loop effects | $hgg$ loop effects: | | | | |
| | scalar triplet | 0.16 | 0.31 | 0.37 | 0.52 |
| | scalar octet | 0.39 | 0.75 | 0.92 | 1.3 |
| | vector octet | 1.8 | 3.5 | 4.2 | 5.8 |
| | $h\gamma\gamma$ loop effects: | | | | |
| | scalar triplet | 0.15 | 0.18 | 0.24 | 0.36 |
| | scalar octet | 0.25 | 0.29 | 0.39 | 0.60 |
| | vector octet | 1.1 | 1.3 | 1.8 | 2.7 |
| | Vector-like leptons | — | — | 1.2 | 1.5 |

# Summary

Higgs precision data can be sensitive to multi-TeV scales,
beyond the reach of direct LHC searches, unless minimally
weakly coupled scenario ($\leftarrow$ complement LHC searches).
Pattern of deviation carries additional information on BSM physics.
LHC+LC coupling measurement $\rightsquigarrow$ unique window into BSM.

Work has only started!

# Thank You For Your Attention!